Application of the overall equipment efficiency technique and theory of constraints to minimize Bottlenecks in a production line

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***Abstract**-One of the biggest concerns of the industries is to align the production flow with the demand, therefore, the main focus is to adjust all the processes so that they operate at the maximum installed speed, without generating bottlenecks. to ensure the reduction of waste, especially those related to the consumption of electricity. In this sense, this work aims to identify the production bottlenecks of the manual insertion process of the components - BMI of a factory in the Industrial Pole of Manaus, to apply the theory of restrictions - TOC and the Overall Equipment Efficiency index - OEE of the equipment. Based on the results obtained, it was possible to identify the bottlenecks and restrictions of the system and to propose suggestions for improvements in the process, in addition to improving the overall equipment efficiency index of the welding machine through fine adjustments in its setup, as well as software and hardware acquisitions. Installing sensors on the assembly line for monitoring and improving process and maintenance.*

Keywords-Bottlenecks, Overall Equipment Efficiency Index, Theory of Constraints.

I. INTRODUCTION

From the first Industrial Revolution onwards, subsequent revolutions resulted in significant changes in manufacturing processes from water and steam powered machines to automated, electrical and digital production. As a result, advances in manufacturing process technology have become increasingly complex, automatic, and sustainable by operating machines in a simple, ceaseless, and efficient way [1] and [2].

According to Rashid and collaborators [3], changes in organizations are evident in all operational aspects. They need to improve their processes and their business model to meet demands and remain in the highly competitive market.

However, any industry, company or service provider is subject to restrictions that affect and limit the production process, known as bottlenecks, strangulation, or restrictions [4].

According to Chase and colleagues,[4] the bottleneck, constraint or strangulation are designations given to components that limit the performance or capacity of a productive system. In addition, in a production process, the bottleneck is the activity with the lowest production capacity, preventing the company from fully meeting the planned demand [5]. The bottleneck is characterized as the slowest resource, in short, it is the one with the longest delay.

The restrictions are related to the operations of the equipment, which can generate some unforeseen events and become bottlenecks. For example, if an equipment has a market demand of 150 hours, but the availability is 200 hours, it is considered a non-bottleneck resource. However, if the equipment has difficulty maintaining this total availability, it is considered a restriction [6].

The problems caused by excess or lack of productive capacity exist in all companies, however, they can be minimized by scaling the investment in machinery and equipment in parallel with the management of bottlenecks or restrictions in the productive sectors [7] and [8].

The work aims to investigate the bottlenecks or restrictions of a production line of electronic products and to apply OEE with the TOC in the Manual Component Insertion (IMC) process to reduce waste. For example, in

the case where one of the resources of operations is considered slow, causing material and financial losses.

Therefore, to observe the bottlenecks of a slab production line and suggest new ways to minimize it, using the Theory of Constraints (TOC) aligned with the calculation of the Overall Equipment Efficiency Index (OEE), more specifically in the operations of the welding machine, with the aim of improving and guide the sectors involved in improving the manufacturing process.

II. BACKGROUND

2.1 Production Systems

According to Moreira and collaborators [9], the production system is a set of activities and interrelated operations involved in the production of goods (case of industries) or services. Some fundamental constituent elements are distinguished in the production system. They are the inputs, the creation or conversion process, the products and or services and the control subsystem. In this way, it can be said that a system is any activity or set of activities that receives an input (Inputs), usually raw materials, adds value to it and provides as a result the creation of products or services that are the outputs, to a particular customer [10].

In this sense, productive systems are taking on an important role in modern society [11]. Thus, the market demands continuous improvements in products in terms of quality, delivery costs, which can only be achieved in a flexible environment, capable of changing quickly, adapting to the process without losing its reliability [12] and [13].

Thus, the provision of efficient alternatives for the use of resources in their activities and support for the productive system's capacity for flexibility seems to be relevant for production management [14]. Intelligent production systems, as well as adapted engineering methods and tools are an important factor in successfully programming distributed and interconnected production facilities in future Intelligent Factories [14] and [15].

Smart factories combined with emerging technologies such as: Internet of Things, Intelligence and Computer Vision etc. They lead the organization to evolve in the maturity levels of Industry 4.0.

Thus, the exchange of data and information between devices in real time is the fundamental element of smart factories, as these data represent production status, electricity consumption behavior, material handling, customer orders, feedback, supplier data, etc. [15].

2.2 DMAIC Method

The DMAIC method, whose acronyms are: Define, Measure, Analyze, Improve and Control, came up with the task of reducing variations in manufacturing processes and aims to improve the process through the correct selection of projects and with steps directed to solving problems in a cyclical and continuous way [16], [17] and [18].

According to Escobar [19], the use of the DMAIC methodology is able to promote the reduction of defect and failure rates in products or services and processes, as well as in increasing productivity, reducing costs, among others. The five stages and their main characteristics are detailed below according to [20].

Defining is the first stage of DMAIC, which consists of identifying the critical processes responsible for generating bad results and defining the project's goal. Through the history of the problem and the presentation of possible restrictions and assumptions, as well as the work team is formed and the preliminary project schedule is defined.

The Measure is the second step of the method, because with the problem refined or focused, the team decides between collecting new data or using the existing ones in the company. In this step, data collection is essential to validate and quantify the problem or opportunity, aiming at defining priorities and making decisions about the criteria that are necessary [21].

Analyzing is the third step, in which the identification of the variables that affect the process is carried out, and it is necessary to find the causes of the problem by delving into the details, identifying its critical activities [21].

Improving is the fourth stage of DMAIC Initially, clear and objective proposals are created to solve and eliminate the causes found in the Analyze stage, of the identified problems. According to [22] the guarantee of improvement in the process is associated with a solution that is able to eliminate and prevent the occurrence of problems. Thus, ideas and solutions are analyzed, prioritizing potentials, assessing and minimizing their risks.

Controlling is the last step of the method, in this step the implementation of the improvement is confirmed, the problem is solved, the validation of the benefits achieved, the necessary changes to the procedures and work instructions, the implementation of the control tool, ending with the audit of the process and performance monitoring [23].

In summary, according to the author [24] DMAIC, if well used can increase the efficient and the profitability of companies making them more competitive.

2.3 Theory of Constraints

The Theory of Constraints (TOC) was developed by Eli Goldratt, to manage bottlenecks or restrictions in the

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productive sectors [7]. In general, the TOC consists of a production scheduling system created from the analysis and restructuring of the restrictions found in the line [25].

According to Cox and collaborators [26], TOC is a theory rich in terms of actions, which can be developed in the current principles and methods that support the production sectors, being applicable in the identification of bottlenecks, as well as in any sector of the company.

For the Bertaglia,[27] the main idea of TOC is based on the fact that every tangible system has at least one restriction. Restrictions are factors that prevent resources from reaching the goal, they are responsible for determining the maximum levels of system outputs.

In short, restrictions can be any element or factor that prevents a system from achieving its performance with respect to its demand [25]. According to Caulliraux and colleagues, [28] TOC starts from the premise that in every system there is a bottleneck. However, to identify the bottleneck, an articulated view of the entire process is necessary. Thus, this vision is built from a network that represents resources, products, times, etc. [29].

Accordingly, Cox and collaborators, [26] the five steps to identify bottlenecks are:

1st Step: Identify the bottleneck or restrictions of the system, that is, the resource with the lowest capacity defines the maximum capacity of the system;

2nd Step: Decide how to exploit the system constraint, that is, maximize the performance of the system, in order to make the most of it;

3rd Step: Subordinate the entire system to what was decided in the 2nd step;

4th Step: Raise the system constraint;

5th Step: Return to the 1st step if the restriction is removed in any previous step and does not allow inertia to act again in the process.

The authors [30] show that many restrictions happen in operations involving machines that consume a lot of time for preparation. In this case, it is necessary to use quick changes and work with larger batches. Therefore, an hour lost in a bottleneck results in a loss in the entire production system, that is, a waste of time.

2.4 Bottlenecks

Bottlenecks, restrictions or bottlenecks are designations given to components that limit the performance or capacity of an entire production system [4].

According to De Paula Pessoa and collaborators [5] the bottleneck is any block in the production system that limits, determines its performance and its ability to obtain revenues for the company, that is, the bottleneck is the stage with the lowest productive capacity preventing the company in fully meet planned demand.

The author [31] points out that the bottleneck is the slowest activity in a production chain, although it can, in most cases, be a machine or part of the information flow, such as order processing.

For the authors [32], bottlenecks are defined as the operation performed on a given equipment that has less capacity for net production of goods, such as parts, circuit boards, services etc., restricting the production of the entire line.

Consequently, once the bottlenecks or restrictions in the production line have been defined, it is necessary to investigate and treat them, using tools that measure the OEE of the equipment.

2.5 Global Equipment Efficiency Index

The OEE, from Total Productive Maintenance (MPT) was created so that companies could measure the levels of efficiency of their equipment, being seen as a tool in the implementation of MTP. However, it was only in the late 1980s that OEE came to be recognized as a powerful tool in measuring the performance of equipment in the production system [33].

According to Pacheco and collaborators [34], the OEE is an operational indicator with application at several levels within a manufacturing system. In this way, OEE can be calculated on several production lines, to verify the actual levels of use of the industry's assets [35] and [36].

For the author [37] the calculation of OEE should be applied primarily to resource bottlenecks that restrict industry gains. Thus, the constant monitoring of resource efficiencies will provide relevant information for the elaboration of action plans that aim to reduce the insufficiencies of the productive systems [38]. This index indicates the efficiency of the equipment during its cycle of operations [39]. The calculation is done using Equation 1:

$$\mu_{global} = \frac{\sum_{i=1}^{n} tp_i \times q_i}{T} \quad (1)$$

Where:

μ_{global} = Global operating income index;

tp_i = cycle time of a product i;

q_i = quantity produced of the product;

T = total time available for production

The OEE takes into account factors such as equipment production, availability and cycle time of the operation [39]. However, [38] points out that OEE should not be calculated in the same way for all jobs, as the available time T, to be considered in the equation, depends on whether or not time is a restrictive resource in the production flow.

Thus, the calculation of OEE is considered in the following cases: If the job is a critical resource bottleneck:

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In this case, the denominator OEE is called TEEP- Total Effective Equipment Productivity. Thus, the time T considered in the Equation is the total time, either 24 hours / day or 1,440 minutes / day in the case of critical bottlenecks [40]. This is explained by the fact that, since the workstation is a bottleneck, all the time available must be used in production. Thus, this index indicates the time that can be gained to produce and corresponds to the real productivity of the productive system, from the bottleneck.

If the workstation is a critical resource, no bottleneck: In this case, the indicator is called OEE- Overall Equipment Efficiency. The time T considered in the equation is the time available, obtained by the difference between the total time and the time of the programmed stops. As it is not a bottleneck job, it is possible to schedule stops such as lunch breaks, workplace gymnastics, snacks etc., since the non-stop of this equipment would generate intermediate stocks before the bottleneck. Thus, this index indicates the equipment's effectiveness during the programmed operating time [38] and [34].

In summary, OEE, when applied to the bottleneck resource, can increase the system's gain [41]. In view of this, it can be concluded that the management of bottlenecks or restrictions suggested by TOC, in line with the OEE indicator can contribute to the effective increase in productivity, as well as to the profit of the system [34].

III. RELATED WORKS

The related works presented in this section were cataloged from the bibliographic review database in order to present the concepts and applicability of TOC and OEE.

The authors' work [42] aimed to apply TOC to a manufacturing line, through a case study in a war products industry, together with continuous improvement to reduce losses in the production process of a part, which restricted the production of one of the items produced in the company.

As a result, the authors applied TOC to the production line as follows: based on the production times of the company's system and the takt time (production rate), with the relationship between jobs, processing times and the production rate. production of each post.

Data collection was performed using the Enterprise Management System (EMS), which was used in the company, in which it was possible to simulate capacity in a graph, using the takt time to locate the system's bottleneck operations in relation to demand. The calculated times were divided into takt time to reach the monthly demand for 1600 products and the other for the goal imposed by the 2000 product team.

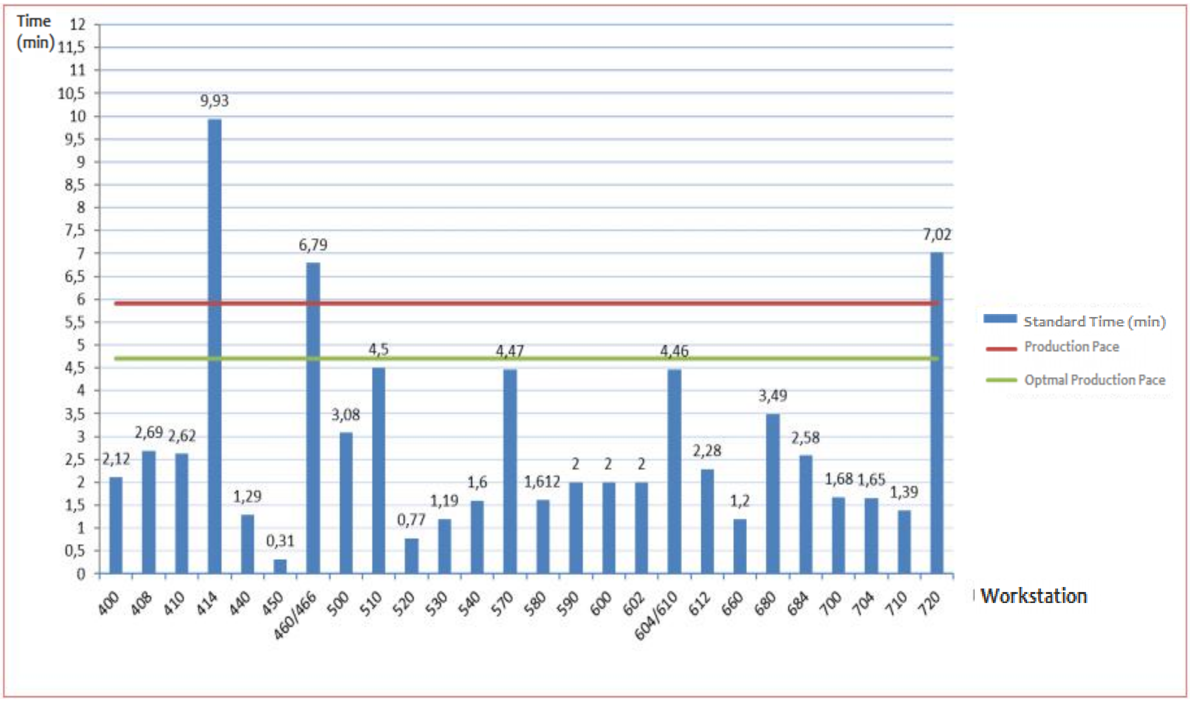

Fig. 1: Company productive capacity

Analyzing the graph of productive capacity, it is observed that three jobs met the demand proposed by the client, among the others, they were: the 414 station with 9.93 minutes; the post 460/466 with 6.79 minutes and the post 720 with 7.02 minutes, since they met above the takt

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time. Fig.1 shows the company's productive capacity, before the TOC application methodology.

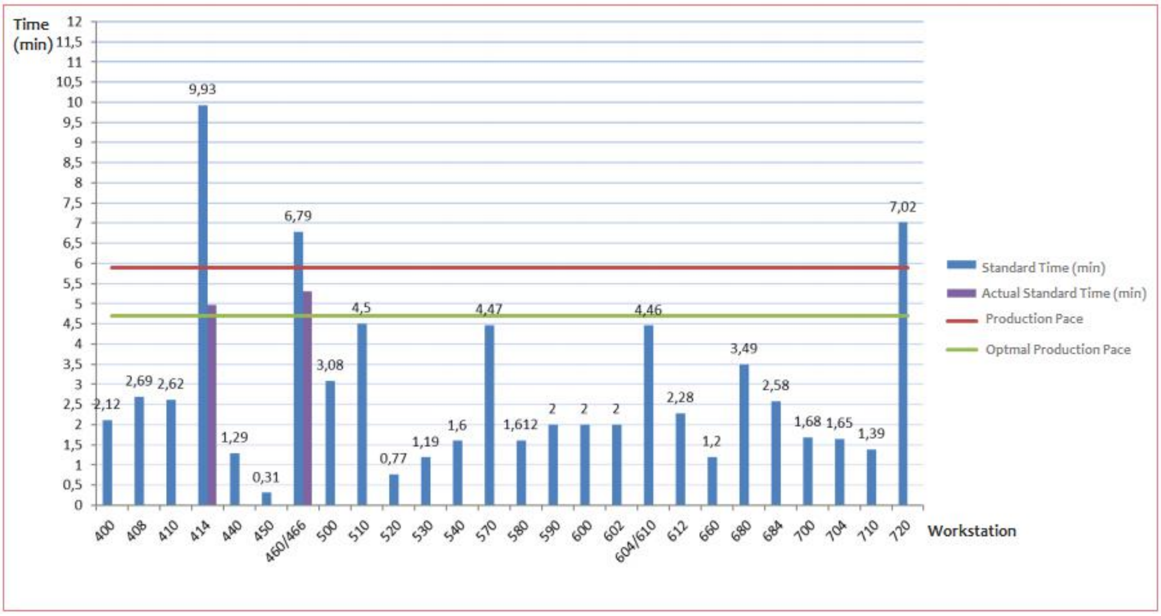

Fig. 2: Company productivity index

With the application of TOC methodology, productivity was higher, as shown in Fig.2, obtaining an increase of 80% with improvement, operational leverage of 37 products / day, the time of crossing parts dropped from 77.75 to 67.02 minutes , disregarding the movement time and Working in Process (WIP) won around 12%, in just three posts.

In the authors' work [39], a case study was presented in the production process of a manufacturer of capacitors resistant to high vibrations in the automotive industry. The objective was to find the path of efficiency, measuring the production cycles to identify flawed points, and then to propose actions aimed at the growth of OEE.

The authors balanced the flow, reduced losses and continued improvement. Data collection was carried out by monitoring the manufacturing sector for special elephant and soldering star capacitors.

The application of the method allowed to identify the bottleneck operation and other limiting points of the process, contributing to the leverage of efficiency in the company. As a result, the authors obtained eight types of tasks that represented losses, being classified into five distinct types: transportation, processing, defective product, stock and waiting.

The authors obtained as a result the excesses of rework and inspection of 84.5% while the operations that transform the capacitor were 15.5%. While the versatility of the welding process was the main cause of the failures, since 37.5% of its activities that do not add value are due to the inefficiency of this equipment. According to the graph in Fig.3, the loss from defective products is the sector that most occurs in the system.

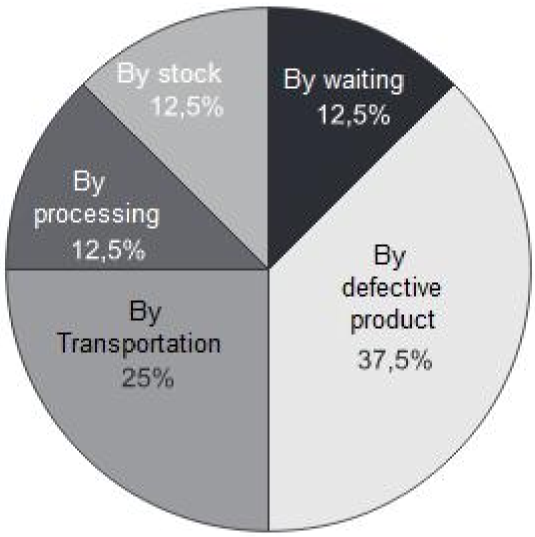

Fig. 3: System loss analysis

In addition, focusing on the optimization of the Capacity Restriction Resource (RRC) and the bottleneck, they obtained an increase of approximately 20%, as the current production increased from 3,500 to 4,189 pieces per shift.

In the work of Wolniak and collaborators [43], a study was presented with practical application of TOC to

improve the production process, in a company that produces electrical equipment to serve the mining industry. The equipment produced by the studied company is electrical equipment with dustproof enclosures, services related to the production of electricity and air conditioning systems for underground mining facilities.

The sector of the company in which the study was applied was the painting department, identified as a bottleneck with great financial and material loss, as well as customer complaints about product quality.

The focus of the work was divided into two aspects of the implementation of TOC. First, a new way of organizing work inside the painting shop was developed, according to table 1 presented below.

Table.1: Change in the working hours of the painting sector

Before implementation	After implementation	Duration
2nd Shift 22: 00-06: 00	2na shift 18: 00-02: 00	8 hours
Lack of a break between shifts	Break between shifts 02: 00-06: 00, possibility of overtime when problems occur, drying the device after completion of work by the painter	4 hours
1stshift 06: 00-14: 00	1st shift 06: 00-14: 00	8 hours
Lack of drying after completion of work by the painter	Drying the devices after completion of work by the painter 14: 00-18: 00	4 hours

By employing changes in the paint shop in the second shift and by inserting an additional four (4) hour interval between shifts, as well as additional drying after the second shift, the company achieved an increase in efficiency of around 19% for a work shift.

By adding the possibility of overtime in the production process in the painting sector, the study made it possible to optimize the sector, enabling him to work 24 hours a day in shifts.

The second change applied was in terms of the quality of the painting of the products, but specifically in the validation of the double painting, in which the product was painted disassembled and subsequently assembled.

The application of TOC in the production process analyzed by the authors allowed to eliminate bottlenecks and reduced the painting process of the pieces from eight to seven stages and the duration time from 1,145 to 1,051 minutes.

The related works presented in this work were compared according to the use of the TOC, DEMAIC and OEE tools regarding the approach used to improve the evaluated processes.

It is possible to observe that the use of TOC, DMAIC and OEE appear separately applied in the presented works and that only in [39] is the joint use of the two methodologies, TOC and OEE, in a case study of an automotive industry, which resulted in the reduction of losses and continuous improvement of the process, which is a good indicator for applying the methodologies together as proposed in this work.

The difference of the proposal of this work in relation to the other related works is in relation to the suggestion of improvements in the processes involving the DMAIC, OEE and TOC together to identify the bottlenecks and propose improvements in the process.

IV. METHODOLOGY

According to the author [44], scientific research is a reflexive and critical procedure in the search for answers to problems not yet solved. Thus, this research is characterized as action research, which aims to understand and intervene in the situation, with a view to changing it.

Action research is defined by a type of research with an empirical basis, which is carried out and conceived in close association with an action or with the resolution of a collective or individual problem, in which researchers and participants are cooperatively involved [45] . Thus, while performing a diagnosis and analyzing the problem, action research proposes changes that lead to the improvement of the analyzed processes [46].

The methodology for the development of this research consists of four phases. In the first phase, the search for articles that make up the bibliographic review was performed, which served as the basis for the development of this work.

In phase two, after the bibliographic review, the production operations related to the IMC process were analyzed, the production cycles were observed, considering the beginning and end of the cycle according to the guidelines on the operation sheets.

In the third phase, the analysis of the BMI process was carried out, in order to monitor the operations to identify possible bottlenecks or restrictions. Subsequently, data collection was carried out through observations of the process, interviews and survey of cycle times for each operation. In this stage, tools such as OEE were used to

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assist in the continuous improvement of processes and equipment, the DMAIC method in identifying times, and the application of TOC principles.

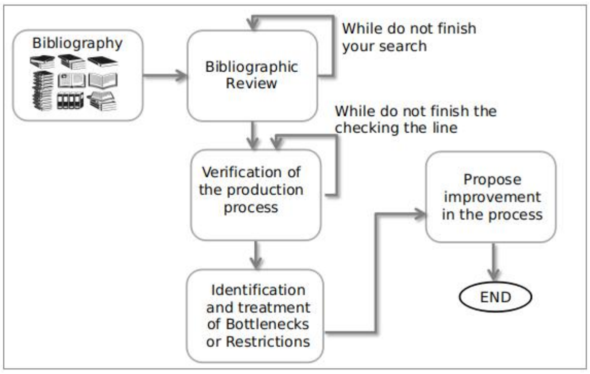

Fig. 4: Flow of the adopted methodology

The fourth phase consists of proposing improvements in the process based on the OEE calculation. Fig. 4 shows the flow of the steps of the methodology proposed in the work.

V. ANALYSIS OF THE RESEARCH RESULT

The company's manufacturing process uses Surface Mounting Technology (SMT). The SMT process begins with the Automatic Insertion of Components (IAC) on the Printed Circuit Board (PCI) to which the Surface Mounting Devices (SMD) components on the PCI are applied, by means of automatic insertion machines, known as pick-and- place. The next step is to make the plate go through the solder remelting oven, to fix the components on the PCI.

Subsequently, the plate goes to the Manual Component Insertion (IMC) process, where the components are inserted in which the machines cannot run in the IAC process. The process is finished with Final Assembly and Testing (MTF) of the plates, where they are performed tests to guarantee the functionality of the produced board, proceeding to the final packaging and transportation.

The IMC process studied it's composed by a production line.the batch consists of 36 boards per box and when completing a pallet (four boxes) they are sent to the MTF. Fig.5 shows the flow of the manual insertion process of the components.

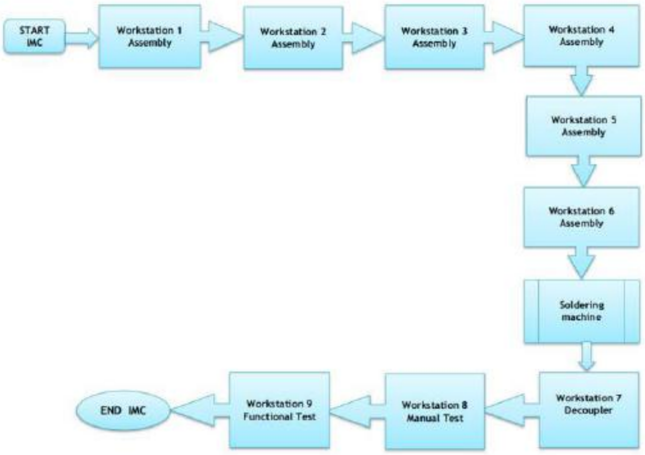

Fig. 5: Flow of the manual insertion process of the components

The IMC process starts from the output of electronic boards from the IAC process. This process is directed to the manual insertion of the components in the PCI, each board has positions defined according to the project, where the electronic components must be allocated.

The first six posts are responsible for inserting the Pin Through Hole (PTH) which means “terminal inserted into the hole” in the PCI. Although, with all the resources available in the IAC process, there are still other PTH components, which depend on manual assembly, as they do not fall within the component categories radial, jumpers, axial and SMD. After the components are mounted on the board, the last post is responsible for doing the overhaul test and packing.

After reviewing the last workstation, the board is directed to the welding machine, using a belt. The welding machine is responsible for fixing the components to the PCI. Thus, before entering the machine the board receives a spray, which is responsible for promoting the cleaning of the surface and the terminals, to avoid oxidation of the same and to ensure the quality of the PCI before passing through the welding tank.

Subsequently, the PCI goes on to preheat, in which the solder flow is activated to occur the deoxidation and cleaning of the board, after which it is directed to the passage in the melted solder tank.

Wave soldering is used in this process of fixing the electronic components on the board. In the process there is also manual welding, in which it is directed to necessary rework in the post-assembly of the board or for maintenance during the manufacturing process. Fig.6 shows the welding machine used in the IMC process line and the object of study in this work.

After the board leaves the machine, an operator is responsible for uncoupling it from the pallet and passing it through the scanner to count the number of boards.

Fig. 6: Welding machine

The next stages are related to the tests board inspection, the first is the manual and visual test, performed by three operators who analyze the boards, in this test a magnifying glass, good lighting and manual welding is used for possible reworks or flaws found on the board.

The second test is the functional test, used to eliminate defects in assembly and design because it checks the dynamic behavior of the circuit. This test is used at the end of the line to identify whether the circuit board mounted printed passed or failed. At the last station, an operator is responsible for applying the silicone glue to the board, to fix the components and then read them on the scanner the signs up until finalization of the batch. Fig.7 shows an example of a printed circuit board with welded components.

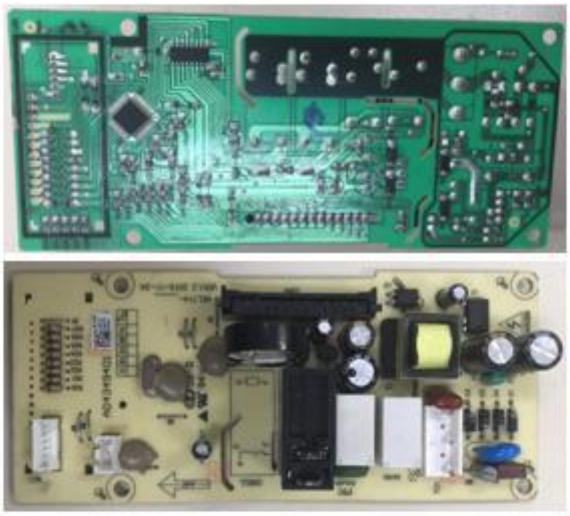

Fig. 7: Printed circuit board with soldered components.

This study was supported by the Production Engineering sector and the Factory Maintenance sector in the follow-up during visits.

Based on the on-site assessment and observations of the production line of electronics and informatics it was possible to define the data collection methods together with TOC, to identify bottlenecks and line limitations and subsequently propose improvements.

The DMAIC and OEE tools were also used to calculate the efficiency and quality of production, regardless of the results obtained in the responsible sectors, the company allowed the measurements to be performed with production in full operation and data collection in real time.

Monitoring in the company it was for four months and visits were divided once a week, in order to learn about the IMC manufacturing processes. The work was guided by the DMAIC tool, which is part of the Six Sigma methodology that directed bottleneck identification activities, to be later applied to TOC.

Observing Table 2, it is noted that the steps defined in the line verification were thought from the definition that is the first step of the DMAIC method, with the applications of TOC and the measurement with records and process mapping, and the analysis by timing each station on the production line to check the causes of bottlenecks and propose the necessary changes, aimed at improving and controlling waste.

For better targeting, the data for analysis were collected from the timing of the assembly times of the electronic components on ten boards.

Table.2: DMAIC methodology steps

Phases	Appetizer	Activities	Outputs
To define	-TOC application -Proposal for improvement	-Identify the bottleneck -Specify bottlenecks -Measure variables	-Definition of the problem - Project scope
Measure	- Records of the BMI process - Mapping the IMC process	- Collect data - Integrate data - Making tables and graphs	-Table with operating times for each workstation -Time charts of each workstation

Analyze	-Table with the operating times of each workstation -Time chart for each workstation	-Raise possible causes -Investigate the root cause -OEE calculation	- Root cause the generation of bottlenecks or restrictions
Improve	- Root cause of bottlenecks -OEE	- To propose improvements - Propose corrective actions	- Process improvement
Control	- Improvement of the process	-Meetings and accompaniments	- Effectiveness of the process through OEE and TOC

Table 3 presents the raw data collected from the production line for a given board model with the total thirteen jobs. The data were timed and transformed into the unit of seconds to facilitate OEE calculations.

Workstations were given letters of the alphabet from A to N, to maintain the confidentiality and integrity of employees who had their production times accounted for. To maximize collection, all stations were monitored and timed ten times, where P1 corresponds to the mounting board (board 1) to P10 (board 10), thus, the times were divided by the amount of collections made, and with that it was possible to obtain the average time for each station.

The evaluation of the data was on the first line from the non-automated workstations, considering the time of insertion of components on the board of each assembler and the position of the welding machine where the time of entry of the plate into the machine until its exit was evaluated , ending with the collection of testing time and the application of silicone and packaging.

Thus, as the object of study of the work is the welding machine, the timed time was from the entry of the plate in the automatic welding until its exit from the machine, totaling ten welded boards.

Table.3: Data collected from the production line.

Line 01											
Model plate	**Time in seconds (s)**										
Workstations	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**	**P10**	**Average**
A	14	13	15	26	21	15	21	13	26	20	18.4
B	14	17	15	18	19	17	18	15	19	15	16.7
C	18	15	17	18	19	17	15	18	18	19	17.4
D	18	22	18	15	19	18	22	18	15	18	18.3
E	11	11	13	11	9	11	12	11	13	14	11.6
F	8	14	14	16	14	14	16	14	14	16	14
Soldering Machine	136	137	138	137	136	137	137	138	137	136	136.9
H	11	10	7	9	7	11	11	10	7	9	9.2
I	34	19	30	47	21	34	30	19	47	21	30.2
J	11	19	16	20	17	19	16	17	20	19	17.4
L	86	79	89	86	84	86	86	84	89	91	86
M	77	81	89	81	77	81	89	97	88	89	84.9
N	11	10	18	14	14	18	14	14	18	14	14.5

During measurements, although the entire welding process is automatic, variations in operating time between 136 and 138 seconds were observed. It was also observed that this station is the one that demands the most time in the process, since in addition to welding, the plates undergo a flow of cleaning, preheating and ends with the cooling process until they arrive at the uncoupling station.

The graph shown in Fig. 9 shows the variations in the cycle times of the process, noting that it is not constant. This happens, because the operator of the previous station sometimes holds the process flow by pausing the conveyor, causing variation.

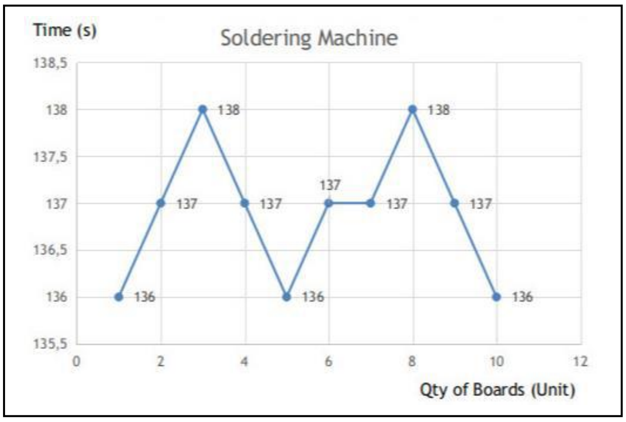

Fig. 9: Graphic of the welding machine

In addition to evaluating the operating time for each part produced at the welding machine station, it was necessary to calculate the OEE, which is obtained by multiplying the calculation of the performance, quality and availability of the equipment. Thus, it was identified that the welding machine has an overall efficiency rate of 73.43%.

Availability was obtained through Equation 2, where TC is the equipment load time given in hours and TPNP is the time of unscheduled stops. Applying the values obtained from the equipment specifications and data collections, TC = 3 hours and TPNP = 0.16 hours, the result is 0.95, which is equivalent to the availability of the equipment.

$$D = \frac{TC - TPNP}{TC} \qquad (2)$$

The Performance is calculated using Equation 3, where QPP is the quantity of parts produced multiplied by TT, theoretical time and divided by TO, equipment operating time given in hours. Applying the values obtained from the equipment specifications and data collections, QPP = 26 pieces, TO = 8 hours and TT = 24 hours, the result of 78.0 is obtained, which is equivalent to the performance of the equipment.

$$P = \frac{QPPxTT}{TO} \qquad (3)$$

Quality was obtained using Equation 4 where PT is the total production subtracted losses and scrap PR divided by total PT production. Applying the values obtained from the equipment specifications and data collections, PT = 210 pieces, PR = 3 pieces, a result of 0.99 is obtained, which is equivalent to Production Quality using the equipment.

$$Q = \frac{PT - PR}{PT} \qquad (4)$$

The total OEE index of the equipment is obtained by multiplying the results of availability, performance and quality. Thus, Equation 5 is used to perform this calculation resulting in 73.35% of the equipment's overall performance.

$$OEE = \quad AvailabilityxPerformancexQuality \qquad (5)$$

The evaluated data of the welding machine station show variations in timing, although in the machine setup the configuration allows to increase or decrease the production speed, however during operation this should not be done, as the operator of the station can pause the belt production to slow down.

The welding machine's OEE was 73.35% and according to the World Class OEE this index should fluctuate between 80% and 85%, because the higher the OEE index, the more efficient the machine is, however this can become a bottleneck, as it dictates the output of the pieces [48].

For the application of the TOC, a study flowchart was developed involving the identification of restrictions, the definition and ways of exploring them, subjecting the choices to management, leveraging the restriction and eliminating the identified restriction. Therefore, this happens in a cycle during the evaluation of the process. Fig. 10, adapted of the authors [42] demonstrates the flow used in this work.

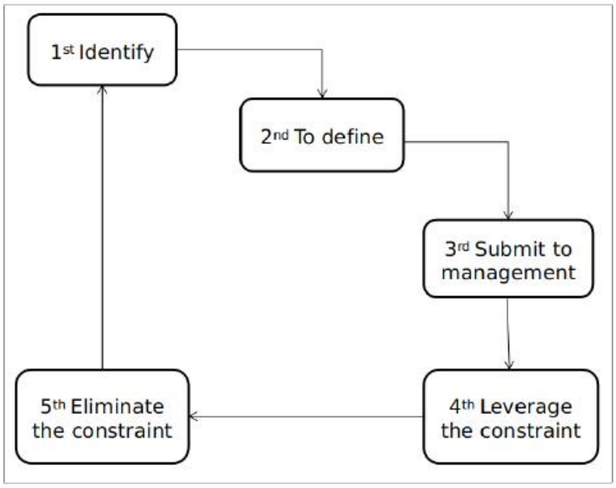

Fig. 10: TOC flow used at work

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For application analysis, the production line stations were grouped and divided into three parts, as follows: the first process with the manual assembly of the components, the second with the welding machine and the third with the tests and application silicone and packaging. Based on the data collected and the evaluations, the automatic welding process was identified as a constraint, based on the OEE.

The automatic welding process was determined and obtained an average time of 136.9 seconds. In step two the constraint was explored and it was calculated that the machine uses 73.4% of its productive capacity, as follows:

- Improvement in the machine setup regarding the belt speed;
- The adjustment of the pallet that supports the plates during the welding process, to reduce unscheduled stops in the event of losses during welding;
- Welding machine monitoring software that allows messages to be sent to maintenance to predict failures, (predictive maintenance with Industry 4.0 and IIoT). In addition to informing the consumption of electricity for the best management of this resource, minimizing waste;
- Decoupling the pallet plates using a robotic machine without the need for an operator (Industry 4.0 and IIoT).

In step three of the flowchart, the suggestions were submitted to the company, and are being implemented. In step four, a forecast was made based on the data collected on how the process can be improved, based on the decrease in the production time of the parts, with the solutions proposed in step two, improving the equipment efficiency index by approximately 12% and , therefore production.

The graph in Fig.11 shows the projection of the improvement of the times of the welding machine in relation to the average of the times collected with the operator and only with the welding machine with automated decoupling.

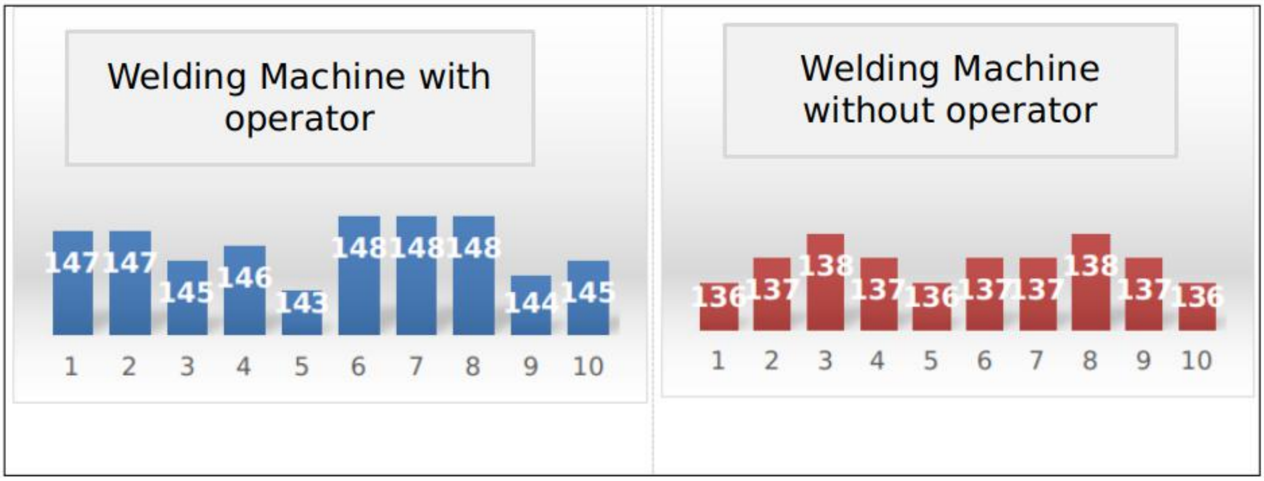

Fig. 11: Projection of improved welding machine times

In step five, based on the projection of the improvements mentioned above, the restriction of the welding machine is removed. Thus, the application of TOC and OEE in the BMI process of the investigated factory allowed the visualization of bottlenecks and restrictions in the production line of electronics and informatics.

Through TOC it was possible to identify and treat bottlenecks as well as suggest changes in the process with the application of training in the production line, interventions in the setup of welding machines and suggestions for the acquisition of software and sensors to adapt the line to the new concepts of the Industry 4.0 and IIoT.

In this way, the application of the concepts enables production managers to check the process continuously, allowing it to be improved with each batch. In addition, it allows the team to be able to optimize production and configure the line more quicklyavoiding waste.

Thus, continuous improvement in the production process is a major factor for the quality of products and, consequently, the company obtains greater profitability.

VI. CONCLUSION

The present work presented the application of the global performance index of the equipment together with the theory of restrictions in the process manual insertion of components of a factory in the Manaus Industrial Pole. Besides that, data were collected from a production line of electronics and informatics in order to identify bottlenecks

or restrictions and treat them using the TOC to then propose improvements in the process.

The results obtained were the improvement of the global efficiency index of the welding machine through fine adjustments in its setup, as well as the indication of the acquisition of monitoring software for maintenance.

As a recommendation for future work, it is intended to expand the study for the application of Industry 4.0 and IIoT in the studied line, and consequently expand to the other lines of insertion of the BMI process.

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